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State-of-the-Art of Combined Cooling, Heating, and Power (CCHP) Systems

1.1 Introduction

With the rapid development of distributed energy supply systems [1, 2, 3, 4], combined heating and power (CHP) systems and combined cooling, heating, and power (CCHP) systems have become the core solutions to improve the energy efficiency and to reduce greenhouse gas (GHG) emissions [5, 6, 7, 8, 9]. The CCHP system is an extended concept of the CHP system, which has been widely utilized in large-scale centralized power plants and industrial applications [10]. CHP systems are developed to conquer the problem of low energy efficiency of conventional separation production (SP) systems. In SP systems, electric demands, which include daily electricity usage and electric chiller usage, and heating demands are provided by the purchased electricity and fuel, respectively. Since no self-generation exists in SP systems, they are proved to be of low efficiency; however, in CHP systems, most of the electric and heating demands are provided simultaneously by a prime mover together with a heat recovery system, a heat storage system, and so on. Energy demands beyond the system capacity can be supplied by the local grid and an auxiliary boiler. If some thermally activated technologies are introduced, for example, absorption and adsorption chillers, into the CHP to provide the cooling energy, the original CHP system evolves to a CCHP system [11], which can also be referred to as a *trigeneration* system and building cooling heating and power (BCHP) system. Since there is no cooling need in winter, the CHP system can be regarded as a special case of the CCHP system. A CCHP system can achieve up to 50% greater system efficiency than a CHP plant of the same size [12].

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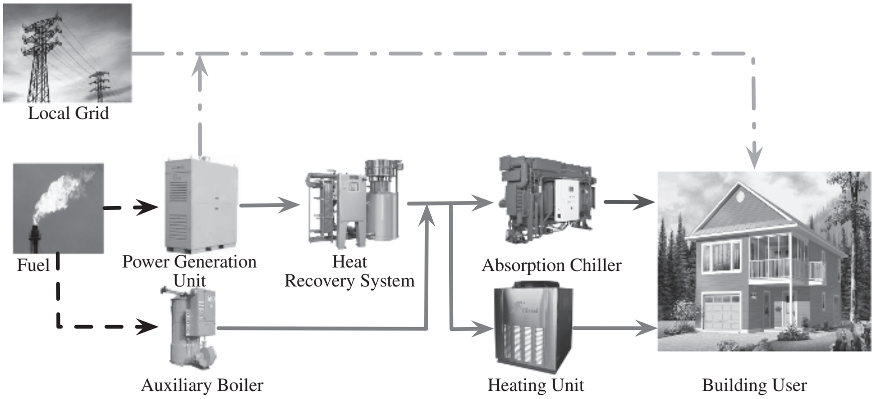

Figure 1.1 A typical CCHP system

A typical CCHP system is shown in Figure 1.1. The power generation unit (PGU) provides electricity for the user. Heat, produced as a by-product, is collected to meet cooling and heating demands via the absorption chiller and heating unit. If the PGU cannot provide enough electricity or by-product heat, additional electricity and fuel need to be purchased to compensate for the electric gap and feed the auxiliary boiler, respectively. In this way, three types of energy, that is, cooling, heating, and electricity, can be supplied simultaneously.

Compared with conventional generating plants, the advantages of a CCHP system are three-fold: high efficiency, low GHG emissions, and high reliability.

First, the high overall efficiency of a CCHP system implies that less primary fuel is consumed in this system to obtain the same amount of electric and thermal energy. In [10], the authors give an example to show that, compared with the traditional energy supply mode, the CCHP system can improve the overall efficiency from 59% to 88%. This improvement owes to the cascade utilization of different energy carriers and the adoption of the thermally activated technologies. As the main electricity source, the PGU has an electric efficiency as low as 30%. By implementing the heat recovery system, the CCHP system can collect the by-product heat to feed the absorption/adsorption chiller and heating unit to provide cooling and heating energy, respectively. By adopting the absorption chiller, no additional electricity needs to be purchased from the local grid to drive the electric chiller in summer, but only the recovered heat is used. In winter, a CCHP system degenerates to be a CHP system. The high efficiency of the CHP system is investigated in [13, 14, 15, 16, 17, 18, 19, 20]. In a nutshell, a CCHP system can dramatically reduce the primary consumption and improve the energy efficiency.

The second advantage involved in the CCHP system is the low GHG emissions. On the one hand, the trigeneration structure of the CCHP system contributes to this reduction. Compared with SP systems, if within the capacity limitation of the prime mover, no additional electricity needs to be purchased from the local grid, which is supplied by fossil-fired power plants. It is well known that, even though the penetration of some types of renewable energy, for example, the wind, tide and solar energy, increase significantly [21, 22, 23], because of their intermittency, the main electricity producer is still the fossil-fired power plant. By reducing the consumption of electricity from the local grid, GHG emissions from fossil-fired power plants can be decreased. Moreover, adopting the thermally activated technologies can also reduce the electricity consumption by the electric chiller, which will result in less consumption of fossil fuel in the grid power plant. On the other hand, new technologies in the prime mover also contribute to the GHG emissions reduction. Incorporating fuel cells, which are one of the hottest topics in recent years, in the CCHP system can increase the system efficiency up to 85–90% [24]. Compared with some conventional prime movers, such as the internal combustion (IC) engine and combustion turbine, the new-tech prime movers can provide the same amount of electricity with less fuel supply and less GHG emissions. In recent years, aiming to reduce GHG emissions, an increasing number of countries have begun to run the carbon tax act [25, 26, 27, 28, 29]. As a result of these acts, reducing GHG emissions can not only reduce the contaminant of the air, but also can improve the system's economic efficiency.

The other benefit brought by the CCHP system is reliability, which can be regarded as the ability to guarantee the energy supply at a reasonable price [30]. Recent cases have demonstrated that centralized power plants are vulnerable to natural disasters and unexpected phenomena [31]. Changes in climate, terrorism, customer needs, and the electricity market are all fatal threats to the centralized power plants [10]. The CCHP system, which adopts the distributed energy technologies, can be resistant to external risks and has no electricity blackouts, for it is independent of electricity distribution. A comparison of the reliability between the distributed and centralized energy systems in Finland and Sweden can be found in [30].

A typical CCHP system consists of a PGU, a heat recovery system, thermally activated chillers, and a heating unit. Normally, the PGU is a combination of a prime mover and an electricity generator. The rotary motion generated by the prime mover can be used to drive the electricity generator. There are various options for the prime mover, for example, steam turbines, stirling engines, reciprocating IC engines, combustion turbines, micro-turbines, and fuel cells. The selection of the prime mover depends on current local resources, system size, budget limitation and GHG emissions policy. The heat recovery system plays a role in collecting the by-product heat from the prime mover. The most frequently used thermally activated technology in the CHP/CCHP system is the absorption chiller. Some novel solutions, such as the adsorption chiller, and the hybrid chiller, are also adopted in CCHP systems [32, 33, 34, 35, 36]. The selection of the heating unit depends on the design of the heating, ventilation and air conditioning (HVAC) components.

With the benefits of high system and economic efficiency, and less GHG emissions, CCHP systems have been widely installed in hospitals, universities, office buildings, hotels, parks, supermarkets, and so on [37, 38, 39, 40, 41]. For example, in China, the CCHP project at Shanghai Pudong International Airport generates combined cooling, heating, and electricity for the airport's terminals at peak demand times. It is fuelled by natural gas from offshore in the East China Sea [42]. This system is equipped with one 4 MW natural gas turbine, one 11 t/h waste heat boiler, cooling units of four YORK OM 14 067 kW, two YORK 4220 kW, four 5275 kW steam LiBr/water chillers, three 30 t/h gas boilers and one 20 t/h as standby for heat supply [43]. In the last decade, the installation of CCHP systems has plateaued. Especially, the development is much slower in developing countries than that in developed countries due to the following barriers: less public awareness, insufficient incentive policies and instruments, non-uniform design standards, incomplete connections with power grid, high price and supply pressure of natural gas, and difficulties in manufacturing equipment [43]. According to a survey by the World Alliance for Decentralized Energy (WADE), the penetration of CCHP systems can be increased by introducing the European Union Emissions Trading Scheme (EUETS) and increasing carbon tax.

This chapter aims to provide some fundamental information and the state-of-the-art of CCHP systems. Analyses and comparisons of system components, suitability scope, operating economy, system configurations and operation strategies are given for the purpose of engineering assessment. This chapter is organized as follows: in Section 1.2, different prime movers for driving the CCHP systems are introduced and compared; three main thermally activated technologies that can be used in CCHP systems to achieve energy cascade utilization are introduced in Section 1.3; Section 1.4 focuses on different system configurations according to the system capacity; in Section 1.5, conventional and novel operation strategies, and system optimization methods are introduced, analyzed and compared; development of CCHP systems in three main countries are discussed in Section 1.6; and Section 1.7 concludes this chapter.

1.2 Prime Movers

A prime mover, defined as a machine that transforms energy from thermal, electrical or pressure form to mechanical form, typically an engine or turbine, is the heart of an energy system. Normally, the output of a prime mover is the rotary motion, so it is always being used to couple with an electric generator. In recent years, the prime movers that are installed the most are gas engines and gas turbines [44]. These two types of prime movers belong to the reciprocating IC engine and the combustion turbine/micro-turbine, respectively. Some other types of prime movers, such as steam turbines, micro-turbines, stirling engines and fuel cells, are also being used in CCHP systems in some particular cases. In this section, emphasis will be put on reciprocating IC engines and combustion turbines/micro-turbines; other types will also be discussed.

1.2.1 Reciprocating IC Engines

A reciprocating engine, also known as a piston engine, is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotary motion [45]. There exist two types of reciprocating engines, that is, spark ignition, which uses the natural gas as the preferred fuel and can also be fed by the propane, gasoline or landfill gas, and compress ignition, which can operate on diesel fuel or heavy oil [46]. The size of the reciprocating engines can range from 10 kW to over 5 MW.

As stated in [47, 48], with the advantages of low capital cost, quick starting, good load following performance, relatively high partial load efficiency and generally high reliability, the reciprocating engines have been widely used in many distributed generation applications, such as the industrial, commercial and institutional facilities for power generation, and CCHP systems. The waste heat of the reciprocating engine, consisting of exhaust gas, engine jacket water, lube oil cooling water and turbocharger cooling [46], can be used in thermally activated facilities in the CCHP system. This energy cascade utilization can efficiently improve the system's efficiency. However, a reciprocating engine does need regular maintenance and service to ensure its reliability [49]. Since the rising level of GHG emissions has become a big concern, applications of diesel fueled engines are restricted for the high emission level of NO_x. Current natural gas ignition engines have relatively low emissions profiles and are widely installed. One example is where HONDA has developed a new cogenerator, which is a natural gas-powered engine, powered by "GF160V". This cogeneration unit can reduce the CO_2 emissions up to approximately 20% [50]. Another classical application of the reciprocating engine example is the CHP plant with IC engines which has been installed at the Faculty of Engineering of the University of Perugia since 1994 [51]. The experimental results show that by introducing the absorption cooler into the plant can dramatically reduce the payback period.

Reciprocating IC engines are quite popular in some applications when working together with an electric or absorption chiller. High temperature exhaust gas from the engine can be used to provide heating and cooling, or to drive the desiccant dehumidifier. Maidment and Tozer [40] analyze a CCHP system for a typical supermarket using a gas turbine and a LiBr/water absorption chiller. They discuss the methodology for choosing the prime mover between a gas engine and a gas turbine. The result shows that this CCHP system offers significant primary energy consumption savings and CO_2 savings compared with conventional heat and power schemes. In [52], the authors assess a CCHP system, which is driven by a reciprocating IC engine, combined with a desiccant cooling system. This system incorporates a desiccant dehumidifier, a heat exchanger, and a direct evaporative cooler. The parametric analysis provided in this work shows that combining the desiccant cooling system can handle both latent and sensible loads in a wide range of climate conditions. The coefficient of performance (COP) of this system is 1.5 times that of the conventional system. Longo *et al.* [53] discuss a CCHP system equipped with an Otto engine and an absorption machine. The exhaust thermal energy is recovered to drive a double-effect LiBr/water cycle, and the heat recovered from the cooling jacket is used to drive a single-effect LiBr/water cycle. In [54], Talbi and Agnew explore the theoretical performance of four different configurations of a CCHP system equipped with a turbocharger diesel engine and an absorption refrigeration unit. The results show the potential of using a diesel absorption combined cycle with pre-inter cooling to achieve higher power output and thermal efficiency among other configurations. The situation of CO_2 emissions of CCHP systems with gas engines under different working conditions is discussed in [55].

1.2.2 Combustion Turbines

The combustion turbine, also known as the gas turbine, is an engine in which the combustion of a fuel, usually the gas, occurs with an oxidizer in a combustion chamber [56]. Combustion turbines have been used for the purpose of generating electricity since the 1930s. The size of gas turbines ranges from 500 kW to 250 MW, which makes it suitable for large-scale cogeneration or trigeneration systems. At partial load, the efficiency of the gas turbine can be unacceptably lower than full-capacity efficiency. As a result, generation sets smaller than 1 MW are proven to be uneconomical [10]. Gas turbines also produce high-quality (high-temperature around 482°C) exhaust heat that can be used by thermally activated processes in CCHP systems to produce cooling, heating, or drying, and to raise the overall system efficiency to approximately 70–80% [57]. Adopting some cycle integration technologies, such as steam injection gas turbines and humid air turbines, can improve the performance of the simple-cycle gas turbine by integrating the bottoming water/steam cycle into the gas turbine cycle in the form of water or steam injection [58].

For GHG emissions, because of the use of natural gas, when compared with other liquid or solid fuel-fired prime movers, gas turbines can dramatically reduce CO_2 emissions per kilowatt-hour [59]. Emissions of NO_x can be below 25 ppm and CO emissions can be in the range of 10–50 ppm. Some emission control approaches, such as the diluent injection, lean premixed combustion, selective catalytic reduction, carbon monoxide oxidation catalysts, catalytic combustion and catalytic absorption systems can also help to reduce NO_x emissions.

One typical application of gas-turbine-based cogeneration or trigeneration systems is for colleges or university campuses, where the produced steam is used to provide space heating in winter and cooling in summer. Another typical application is for the supermarket. In the USA, CCHP systems have been widely installed in supermarkets to improve the system efficiency. Produced steam and heat from the gas turbine is used to drive the food-refrigeration system, which requires a huge amount of cooling energy, and to provide the basic space heating [60]. CCHP systems using gas turbines have attracted a certain amount of attention. Exergy analyses for a combustion-gas-turbine-based power generation system are addressed in [61], which can be used for engineering design and component selection. Investigations of CCHP systems using gas turbines can be found in [7, 62]. In the latter, a micro-CCHP system with a small gas engine and absorption chiller is built in Shanghai Jiao Tong University with the designed energy management method, which can also be used in large-scale CCHP systems whose overall efficiency can be as high as 76%.

1.2.3 Steam Turbines

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam, and converts it into rotary motion [63]. Compared with reciprocating steam engines, the higher efficiency and lower cost make steam turbines have been used for about 100 years. The size of steam turbines can range from 50 kW to several hundred megawatts for large utility power plants [64]. Because of the low partial load electric efficiency, steam turbines are not suitable for small-scale power plants. In the US and some European countries, steam turbines have already been widely installed in large-scale CHP/CCHP systems. If well maintained, the life of a steam turbine can be extremely long, and can be counted in years.

The working principle of the steam turbine is different from those of reciprocating IC engines and combustion turbines. For the latter two, electricity is the product and the heat is generated as a by-product. However, for the steam turbine, electricity is generated as the by-product. When equipped with a boiler, the steam turbine can operate with various fuels including clean fuels, such as natural gas, and other fossil fuels. This dramatically improves the flexibility of the steam turbine. In CHP/CCHP applications, the low pressure steam can be directly used for space heating or for driving thermally activated facilities.

GHG emissions of the steam turbine depends on the fuel it uses. If using some clean fuel, that is, natural gas, and adopting some effective emission control approaches, GHG emissions can be relative low. However, the low electric efficiency and long start-up time restrict the installation of steam turbines in small-scale CCHP systems and distributed energy applications [10]. Thus, steam turbines are only considered for being utilized in large-scale industries.

1.2.4 Micro-turbines

Micro-turbines are extensions of combustion turbines. A micro-turbine manufactured by Capstone Turbine Corporation is shown in Figure 1.2. The size of micro-turbines ranges from several kilowatts to hundreds of kilowatts. They can operate on various fuels, for example, natural gas, gasoline, diesel, and so on. One important characteristic of the micro-turbine is that it can provide an extremely high rotation speed, which can be used to efficiently drive the electricity generator. Because of the small size, micro-turbines are suitable for distributed energy systems, especially for CHP and CCHP systems. In the CCHP system, the by-product heat of the micro-turbine is used for driving sorption chillers and desiccant dehumidification equipment in summer, and to provide space heating in winter. The designed life of micro-turbines ranges from 40 000 to 80 000 hours [65, 66].

Another key advantage of the micro-turbine is the low level of GHG emissions; this is due to the *gaseous fuels feature lean premixed combustor* technology. In addition, low inlet temperature and high fuel-to-air ratios also contribute to emissions of NO_x of less than 10 ppm. According to the data in [65], despite the stringent standard of less than 4–5 ppmvd of NO_x, almost all of the example commercial units have been certified to meet it.

Even with the drawbacks of higher capital costs than reciprocating engines, low electrical efficiency, and sensitivity of efficiency to changes in ambient conditions, the compact size and low weight per unit power, a smaller number of moving parts, lower noise, multi-fuel capability [67] and low GHG emissions still make the micro-turbine a popular prime mover in distributed energy systems. Analyses of CHP/CCHP systems installing micro gas turbines can be found in [67, 68]. The former discusses the

Figure 1.2 Capstone C200 micro-turbine with power output of 190 kW

potential of using micro-turbines in CCHP systems in distributed power generation. If the high capital cost and low efficiency can be solved, the market potential could increase dramatically.

In distributed energy systems, small-scale CCHP systems have been proven to be efficient. Due to the advantages, installing a micro-turbine becomes the best choice for a small-scale CCHP system. Much work has been done to investigate the performance of using micro-turbines in CCHP systems. Tassou *et al.* [69] validate the feasibility of the application of a micro-turbine-based trigeneration system in a supermarket. Beyond the feasibility, this paper also reveals that the economic viability of the system equipped with micro-turbines depends on the relative cost of natural gas and electricity. Karellas *et al.* [70] propose an innovative biomass process and use it to drive a micro-turbine and a fuel cell in a CHP system. The system efficiency can be extremely high when the gasification of biomass happens at high temperature. The innovative concept in this paper can be utilized in Biocellus. In 2002, the Oak Ridge National Laboratory (ORNL) presented its work of testing a micro-turbined CCHP system. The testing facility consists of a 30 kW micro-turbine for a distributed energy resource, whose exhaust is used to feed thermally activated facilities, including an indirect-fired desiccant dehumidifier and a 10-t indirect-fired single-effect absorption chiller [71]. From the test data, the efficiency of the micro-turbine strongly depends on the output level and ambient temperature, which makes the full power output to be preferred. Bruno *et al.* [72] conduct a case study of a sewage treatment plant, which is a trigeneration system. The prime mover selected in this system is a biogas-fired micro gas turbine. Hwang [73] in his work investigates potential energy benefits of a CCHP system with a micro-turbine installed. This paper gives the options to choose different types of chillers according to different configurations. Velumani *et al.* [74] propose and mathematically model a CCHP system with integration of a solid oxide fuel cell (SOFC) and a micro-turbine installed. This plant uses natural gas as the primary fuel and the SOFC is fed with gas fuel. Other evaluations, analyses and control strategy designs for CCHP systems running with micro-turbines can be found in [75, 76, 77, 78, 79], to name a few.

1.2.5 Stirling Engines

In contrast to the IC engine, the stirling engine is an external combustion engine, which is based on a closed cycle, where the working fluid is alternatively compressed in a cold cylinder volume and expanded in a hot cylinder volume [80]. Two basic categories of stirling engines exist: kinematic stirling engines and free-piston stirling engines. Also, the engine can fall into three configurations: alpha type, beta type, and gamma type [81, 82].

A stirling engine can operate on almost any fuel, for example, gasoline, natural gas and solar energy. Compared with IC engines, stirling engines operate with a continuous and controlled combustion process, which results in lower GHG emissions and less pollution [82, 83]. According to the data in [84], implementing a same capacity of 25 MW, the NO_x emission of the stirling engine is 0.63 kg/MWh, compared with 0.99 kg/MWh of the IC engine. It is worth mentioning that, since the working fluid is sealed inside the engine, there is no need to install valves or other mechanisms, which makes the stirling engine simpler than an IC engine. As a result, stirling engines can be relatively safe and silent when running.

However, some challenges arise when using stirling engines in CHP/CCHP systems. The first one is the low specific power output compared with an IC engine of the same size. High capital cost is also a key factor that restricts its development. Another aspect is the working environment in CHP/CCHP systems. Unlike IC engines, the efficiency of a stirling engine drops when the working temperature increases. The last but equally important one is that the power output of the stirling engine is not easy to tune. Despite the above drawbacks, stirling engines have been installed in some CHP/CCHP applications because of the flexibility in fuel source, long service time and low level of emissions. A small-scale CHP plant with a 35 kW hermetic four cylinder stirling engine for biomass fuels has been designed, created, and tested by the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GesmbH and BIOS BIOENERGIESYSTEME GmbH in Austria [85]. Moreover, SIEMENS collaborated with some European boiler manufactures, such as Remeha and Baxi, to conduct a large field test in 2009 and market introduction in 2010 of micro-CHP systems with stirling engines.

The most promising aspect of the stirling engine that it can be solar driven. Because of the increasing rate of carbon tax and more attention being paid to GHG emissions, the use of solar energy in CHP/CCHP systems gives more opportunities for the stirling engine.

Some theoretical work has also been done to investigate stirling engines installed in CCHP systems. Kong and Huang [84] propose a trigeneration system with a stirling engine installed and claim that this system could save more than 33% primary energy compared with the conventional SP system. Aliabadi *et al.* [86] discuss the efficiency and GHG emissions of a stirling-engine-based residential micro-CHP system fueled by diesel and biodiesel. According to the market assessment, stirling engines have not been widely applied in the CCHP market. To be further used in CHP/CCHP systems, solutions to high capital cost, long warm up time, and short durability of certain parts should be found [87].

1.2.6 Fuel Cells

Another environmentally concerned type of prime mover is the fuel cell. Fuel cells convert chemical energy from a fuel into electricity through a chemical reaction with oxygen or other oxidizing agents, and produce water as a by-product [88, 89, 90]. Compared with other fossil-fuel-based prime movers, fuel cells use hydrogen and oxygen to generate electricity. Since water is the only by-product, fuel cells are considered to be the cleanest method of producing electricity. Because of the few moving parts contained, the fuel cell system has a higher reliability than the combustion turbine or the IC engine [91]. However, some obstacles still exist for the development and application of fuel cells. The production of the materials, that is, oxygen, consumes energy and produces emissions. There are several ways, for example, electrolysis of water and generation from natural gas, to produce hydrogen for fuel cells, however, none of them can avoid both high energy consumption and high emissions. In the current market, there are various types of fuel cell, including proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the previously mentioned SOFC.

In recent years, much work has been done to investigate fuel cells in CCHP systems. The most widely used choice is the SOFC. Tse *et al.* [92] investigate a trigeneration system, which is jointly driven by a SOFC and a gas turbine, for marine applications. The efficiency of the configuration with double-effect absorption chiller can achieve 43.2% compared with 12% for the conventional system. In [93], Kazempoor *et al.* develop a detailed SOFC model, and study and optimize different SOFC system configurations. They also assess the performance of a building integrated with a trigeneration system, which comprises a SOFC and a thermally driven chiller. In [94], an SOFC with the capacity of 215 kW is combined with a recovery cycle for the sake of simultaneously meeting cooling load, domestic hot water demand and electric load of a hotel with 4600 m^2 area. An economic comparison between the trigeneration and SP systems indicates that, due to the lower heating value of the fuel, a maximum efficiency of 83% for energy trigeneration and heat recovery cycle can be achieved. Verda and Quaglia [95] model a distributed power generation and a cogeneration system incorporated with the SOFC. The authors also compare three configurations for this system, based on different choices of refrigeration systems, that is, single-effect absorption chiller, double-effect absorption chiller, and vapor compression chiller, from both technical and economic points of view. Other work on the environmental, economical and energetic analyses of CCHP systems equipped with SOFCs can be found in [96, 97, 98, 99, 100, 101, 102], to name a few. In [103], the authors model the CCHP system with stationary fuel cell systems from thermodynamic and chemical engineering aspects; and optimize the operation for that. Margalef and Samuelson [104] compare two strategies of operating a CCHP system equipped with a magnesium-air fuel cell (MAFC). The first strategy is to blend the exhaust gas with the ambient air; while the other one is to use the exhaust gas to drive an absorption chiller. The result shows that the second strategy is preferred, for the overall estimated efficiency is as high as 71.7%. Bizzarri [105] discusses the size effect of a PAFC system incorporated into a trigeneration system. Investigations reveal that the more the proper sizing is carried out for the highest environmental and energy benefits, the higher the financial returns will be. According to industry analysts Delta-ee, fuel cell CHP units have 64% of the CHP unit sale market, which doubles the results in 2011. It is becoming the most common technology employed in micro-CHP systems. In 2009, Tokyo Gas had success with the first commercialized residential fuel cell CHP systems based on PEFC, that is, ENE-FARM. In April 2013, they released the new version of that unit with lower cost, smaller size and lower CO_2 emission. This technology helps the fuel cell CHP take the market from other CHP prime movers. Ceramic Fuel Cell Limited's 1.5 kW SOFC CHP system, the so-called BlueGen, targets the market of social housing, shared accommodation, school and small business. This system can be beneficial for academic use, for all the data in this system can be pulled out for analyzing. However, feed-in tariffs and financial support are still obstacles for the development of this type of CHP system. California's Self Generation Incentive Program is a good example of incentive design for all policy makers.

The comparisons among different prime movers can be found in Table 1.1.

1.3 Thermally Activated Technologies

The most efficient solution to providing cooling is to utilize the rejected heat instead of electricity. This solution is realized by the thermally activated technology, which is dominated by the sorption cooling. The difference between the sorption cooling and the conventional refrigeration is that the former uses the absorption and adsorption processes to generate thermal compression rather than mechanical compression. One important reason for the CCHP system being efficient and with low GHG emissions is because space cooling and heating can be provided by using the rejected heat from the prime mover along with the electricity generation. This cascade utilization of heat is due to the thermally activated technology. In conventional SP systems, approximately two-thirds of the fuel used to generate electricity is wasted in the form of rejected

Table 1.1 Comparisons among different prime movers

Prime mover	Size (kW)	Pros	Cons	Emissions	Preferences and applications
IC engine	10–5000	Low capital cost Quick start Good load following High partial efficiency High reliability	Regular maintenance required	High NO_x using diesel Natural gas preferred	Working with absorption/electric chiller Small- to medium-scale
Combustion turbine	500–250 000	High quality exhaust heat	Unacceptable low partial efficiency	NO_x 25 ppm CO 10–50 ppm	Applications with huge amount of thermal need Large-scale
Steam turbine	50–500 000	Flexible fuel	Low electric efficiency Long start-up	Depends on fuel	Electricity as by-product, thermal need preferred Large-scale
Micro-turbine	1–1000	Flexible fuel High rotation speed Compact size Less moving parts Lower noise	High capital cost Low electric efficiency Efficiency sensitive to ambient conditions	NO_x <10 ppm	Distributed energy system Micro- to small-scale
Stirling engine	Up to 100	Safer and silent Flexible fuel Long service time Can be solar driven	High capital cost Power output hard to tune	Less than IC engine	Solar driven Small-scale
Fuel cell	0.5–1200	Operate quietly Higher reliability than IC and combustion engine High efficiency	Energy consumption and GHG emissions due to hydrogen producing	Extremely low	Micro- to medium-scale

heat. By introducing thermally activated technologies, the electric load for cooling is shifted to the thermal load, which can be fully or partially achieved by absorbing or adsorbing the discarded heat from the prime mover. The main application of the sorption refrigeration is for CCHP systems in residential buildings, hospitals, supermarkets, office buildings, and district cooling systems [106].

Mainly, three types of thermally activated technologies exist, that is, absorption chiller, adsorption chiller, and desiccant dehumidifier. Since the temperature of the discarded heat from prime movers can lie in different ranges, thermally activated facilities should be chosen to couple with prime movers. For example, if the heat source temperature is around 540°C, then the suitable choice is a double-effect/triple-effect absorption chiller.

1.3.1 Absorption Chillers

Investigations of the absorption cycle began in the 1700s when it was found that ice could be produced by the evaporation of pure water from a vessel contained within an evacuated container in the presence of sulfuric acid [107]. The absorption chiller is one of the most commonly used and commercialized thermally activated technologies in CCHP systems. The difference between an absorption chiller and a vapor compression chiller is the process of compression. Since absorption chillers use heat to compress the refringent vapor instead of mechanically using rotating devices, they can be driven by the steam, hot water or high temperature exhaust gas. As a result, electricity needed for conventional refrigeration can be dramatically reduced, and the noise of the cooling process can be lowered significantly.

The working process of an absorption chiller can be divided into two processes: the absorption process and the separation process. The absorption process is shown in Figure 1.3. The left vessel contains the refrigerant and the right vessel is filled with a mixture of refrigerant and adsorbent. The absorption process of the refrigerant vapor

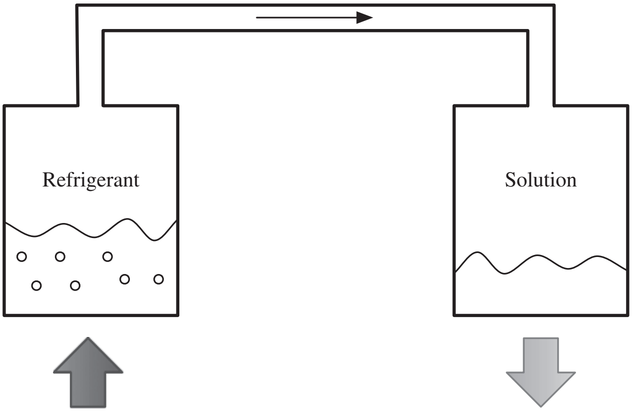

Figure 1.3 Absorption process

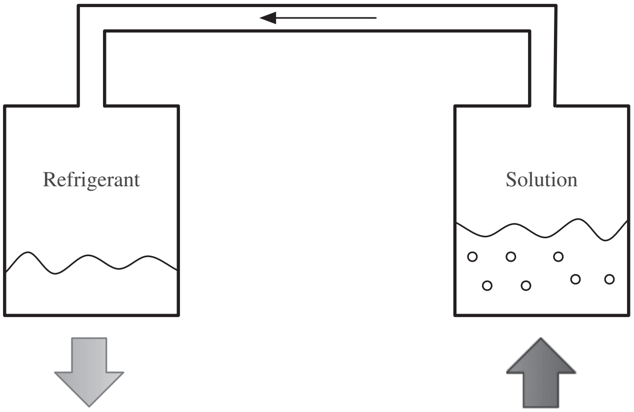

Figure 1.4 Separation process

in the right vessel will cause the pressure and temperature in the left vessel to drop. The temperature reduction in the left vessel is the refrigeration process. At the same time, as a result of the absorption process in the right vessel, heat must be rejected to the surroundings.

As the absorption process continues, the solution in the right vessel gradually becomes saturated. To reatin the ability to absorb, refrigerant must be separated from the solution. Figure 1.4 shows the separation process, which can be regarded as a reverse of the absorption process. Heat from the heat source is used to dry the refrigerant from the saturated or almost saturated solution. The refrigerant vapor is then condensed by a heat exchanger to act in the next cycle of the absorption process.

The chemical and thermodynamic properties of the working fluid determine the performance of an absorption chiller. The working fluid should be chemically stable, non-toxic, and non-explosive. Moreover, in liquid phase, it must have a margin of miscibility within the operating temperature range of the cycle [108]. According to [109], there are around 40 refrigerant compounds and 200 absorbent compounds available for the absorption chillers working fluid. However, the two most commonly used are lithium bromide/water (LiBr/water) and ammonia/water (NH_3/water). Usually, LiBr/water absorption chillers are used in air cooling applications with evaporation temperature in the range of 5–10°C, while NH_3/water absorption chillers are used in small-scale air conditioning and large industrial applications with evaporation temperature below 0°C [106].

In the literature, absorption chillers have been widely installed in CCHP systems. In 2002, the US government awarded Burns & McDonnell Engineering Co. a development contract of building an integrated gas turbine energy system based on improved CHP/CCHP technology. This plant is powered by a 4.6 MW Solar Turbines Centaur 50 gas turbine and two-stage indirect fired Broad Co. absorption chillers [110]. A small-scale CCHP system, installing a micro-turbine and an absorption chiller is demonstrated at the University of Maryland [111]. By adding the absorption chiller in the decentralized SOFC-based CCHP system, with an increased cost of about 0.7% compared with conventional systems, the CO_2 emissions can be reduced by 30%. In [102], a decentralized system with the integration of an SOFC and a double-effect LiBr/water absorption chiller is investigated. In [112], the authors introduce a CCHP system, with three engines and a total electrical power production of 9 MW, which supplies the thermal energy to drive an NH_3/water absorption chiller ARP-M10 by Colibri. This configuration is applied in a margarine factory in the Netherlands, a vegetable freezing factory in Spain, and a dairy factory in Spain. All of the three applications show a cost reduction by using this system.

1.3.2 Adsorption Chillers

The development of adsorption cooling began when the phenomenon of adsorption refrigeration caused by NH_3 adsorption on AgCl was discovered by Faraday in 1848 [113]. Similar to absorption chillers, adsorption chillers make use of the discarded heat from the prime mover to provide space air conditioning. One important difference of an adsorption chiller from an absorption chiller is that the former can be driven by a low temperature heat source. Furthermore, the noiselessness, being solution pump free, the lack of corrosion and crystallization, and small volume make adsorption chillers suitable for CCHP systems, especially small-scale ones [114, 115, 116].

Different from the absorption chiller, in which a fluid permeates or is dissolved by a liquid or solid, the adsorption chiller provides cooling by using solid adsorbent beds to adsorb and desorb a refrigerant. Similar to the two processes in the absorption chiller, temperature of the adsorbent changes according to the refrigerant vapor adsorbed and desorbed by adsorbent beds. A simple adsorption refrigeration circuit consists of a solid adsorbent bed, a condenser, an expansion valve, and an evaporator [34]. The refrigeration process of the adsorption chiller can also be divided into two processes, that is, absorbent heating and desorption process, and the adsorption process. In the first process, the adsorbent bed is connected with a condenser first. Driven by a low temperature heat source, the refrigerant is condensed in the condenser and heat is released to the surroundings. Following that, in the adsorption process, the adsorbent bed is connected to an evaporator, and at the same time disconnected from the condenser. Then cooling is generated from evaporation and adsorption processes of the refrigerant. However, this simple adsorption chiller provides cooling in an intermittent way. To continuously provide cooling, two adsorbent beds should be installed in the system together, in which one bed is heated during the desorption process and the other one is cooled during the adsorption process.

The same as in absorption chillers, adsorption chillers have no internal mechanical moving parts. As a result, they not only run quietly, but also need no lubrication and less maintenance. In addition, adsorption chillers are always made in modules, which makes them suitable for the cooling capacity expansion. Moreover, as mentioned before, since no electricity and fuel is needed to drive the chiller, a low level of GHG emissions is guaranteed. Because of the advantages of the adsorption chiller, research and demonstrations of this type of chiller installed in the CCHP system have been developed widely. Li and Wu [117] discuss the performance of a silca gel/water adsorption chiller in a micro-CCHP system according to different working conditions, especially for different electric loads. In 2000, a CCHP system, equipped with a fuel cell, a solar collector and an integration of a mechanical compression chiller and an adsorption chiller, was installed in the St. Johannes Hospital, Germany [10]. In the same year, a CCHP system with an adsorption chiller began to operate in the Malteser's Hospital, Germany. Shanghai Jiao Tong University (SJTU) has been investigating the applications of adsorption chillers in CCHP systems for many years. In 2004, SJTU set up a gas-fired micro-CCHP system consisting of a small-scale power generator set and a novel silica gel/water adsorption chiller [106].

1.3.3 Desiccant Dehumidifier

A desiccant dehumidifier removes the humidity from the air by using materials that attract and hold moisture. To achieve comfort cooling, sensible cooling, aiming to lower the air temperature, and latent cooling, which means reducing humidity, should be achieved simultaneously. Since, by introducing desiccant dehumidifiers, the control of humidity is independent of the temperature, potentially wasted thermal energy can be used to reduce the latent cooling load and bacteria and viruses can be scrubbed out; desiccant dehumidifiers always operate with chillers or conventional air-conditioning systems to provide comfort cooling and to increase overall system efficiency [10, 118].

Mainly, there exist two commercialized types of desiccant dehumidifiers, which are distinguished by desiccant types, that is, solid desiccant dehumidifier and liquid desiccant dehumidifier. Solid desiccant dehumidifiers are usually used for dehumidifying air for commercial HVAC systems, while liquid desiccant dehumidifiers are popular in industrial or residential applications. Desiccant dehumidifiers are suitable for CHP/CCHP systems, because the regeneration process in the desiccant system provides an excellent use of waste heat [119]. In [120], the authors introduce a CCHP system utilizing the solid desiccant cooling technology. Researchers in Tsinghua University, China, also carried out laboratory research to assess the operational performance and energy efficiency of a CCHP system installing a liquid desiccant dehumidifier [121]. The data collected from summer and winter show that the only way to increase the overall efficiency is to install more waste heat driven equipment to utilize the low-quality waste heat. In [52], the authors assess a desiccant dehumidifier system in a CHP application incorporating an IC engine. Badami and Portoraro [122] analyze the performance of a trigeneration plant with a liquid desiccant cooling system installed at the Politecnico di Torino, Italy. In this paper, the authors provide both the energetic and economic analyses to show the huge potential of using this type of trigeneration system. The desiccant dehumidifier system allows the temperature and humidity in the classroom to be controlled. The air conditioning service can also make this system suitable for academic use. It is proved that with the liquid desiccant cooling system, we can make full use of the waste heat to provide a cooling service in the summer and the overall efficiency can be dramatically increased.

The comparisons among different thermally activated technologies can be found in Table 1.2.

1.4 System Configuration

An economical, efficient and of low emissions CCHP system should be designed with full consideration of energy demands in a specific area, prime mover and other facilities' types and capacities, power flow and operation strategy, and the level of GHG emissions. The selection of facility types belongs to the design of the system configuration, which emphasizes the selection of prime movers according to current available technologies, and on the system scale. It is well known that different climate conditions in different areas lead to different patterns of energy demands. For example, in conventional CHP systems, steam-turbine-based plants are always used as heat plants with electricity generated as a by-product in some cold areas. While in the temperate zone, in summer, the amount of electricity needed by the air conditioning could be huge. Thus, in this kind of area, combustion-turbine-based CHP systems are popular. Some CHP/CCHP applications based on prime mover selections have been mentioned in Section 1.2. The existing CHP/CCHP sites in the market sorted by prime movers are shown in Figure 1.5. With a selected CCHP system configuration, operation strategy is the key to achieve the most efficient way for the CCHP to operate. The operation strategy determines how much electricity or fuel should be input to the system according to the demands; which facility should be shut down to keep the whole system efficient; how the energy carriers flow between facilities; and how much power one facility should operate at. With a designated configuration and an appropriate operation strategy, suitable sizing and optimization can make the system operate in an optimal way. Here, CCHP applications categorized by plant size will be mainly discussed.

Categorized by the rated electricity generation capacity, the CCHP system can have micro-scale (under 20 kW), small-scale (20 kW–1 MW), medium-scale (1 MW–10 MW), and large-scale (above 10 MW).

1.4.1 Micro-Scale CCHP Systems

Micro-scale CCHP systems are the ones with rated size under 20 kW. Recently, much work has been done to investigate and analyze micro-scale CCHP systems, for they are suitable for distributed energy systems. In the literature, Easow and Muley [123] discuss the potential of the micro trigeneration system being applied in the decentralized cooling, heating, and power. By testing an experimental plant, which is a micro trigeneration system with a liquefied petroleum gas driven Bajaj 4-stroke IC engine, the increased energy supply reliability and security, lower energy cost, higher efficiency and less fuel energy loss are verified in this paper. In 2010 in the North Carolina Solar Center, Raleigh, North Carolina, an integrated micro-CCHP and solar

Table 1.2 Comparisons among different thermally activated technologies

Facility	Capacity	Pros	Cons	COP	Preference
Absorption chiller	10 kW–1 MW	Driven by steam Low noise Can be driven by low-quality heat source Low GHG emission	Less efficient than compressor-drive chiller	Up to 1.2	LiBr/water: evaporation temperature 5–10°C NH_3/water: evaporation temperature <0°C Small- to large-scale Double-effect preferred
Adsorption chiller	5.5–500 kW	Driven by steam Small size Noise free Corrosion and crystallization trouble free No lubrication Low GHG emissions	Can only be driven by high quality heat High capital cost	0.6	Small-scale
Desiccant dehumidifier	N/A	Control of humidity independent of the temperature is allowed Reduce the mechanical cooling load	High capital cost Regular maintenance required	N/A	Solid: HVAC systems Liquid: Industrial and residential applications

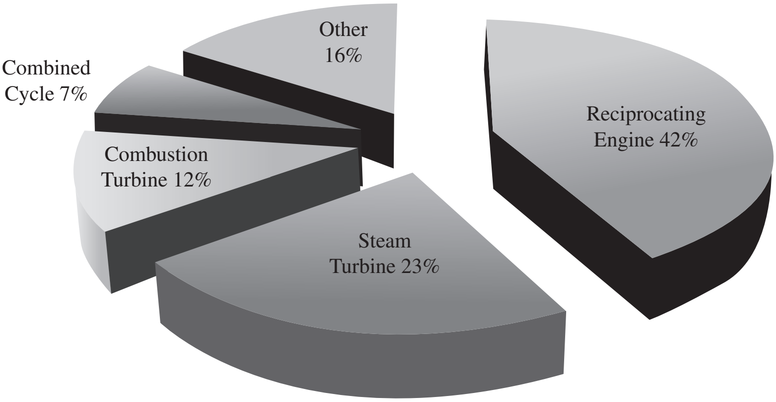

Figure 1.5 Existing CHP/CCHP sites classified by prime movers

system was installed to demonstrate the technical and economic feasibility of incorporating photovoltaic (PV), solar thermal, and propane-fired CHP systems into an integrated distributed generation system [124]. The rated output of the CHP plant, PV, and solar thermal system is 4.7 kW plus 13.8 kW, 5.4 kW, and 4.1 kW, respectively. Thermal energy produced by this system can be used for space heating, domestic hot water, process heating, dehumidification and absorption cooling. With this solar-based CCHP system, CO and NO_x emissions can be reduced to below 250 ppm and below 30 ppm, respectively. Other experimental and test results of micro-CCHP systems can be found in [125, 126, 127], to name a few. In addition, various work on energetic, economic and thermodynamic analyses has been done in recent years. In [128], the authors provide an analysis of matching prime mover heat sources to thermally driven devices in a micro-scale trigeneration system. The T–Q analysis of the prime mover waste heat in this literature also indicates the promise of incorporating micro-turbines, SOFCs and HT-PEMFCs into the trigeneration system. Other analyses can be referred to [129, 130, 131, 132, 133, 134]. Some researchers also focus on the optimization of micro-CCHP systems. Arosio *et al.* [135] model a micro-scale CCHP system based on the linear optimization and incorporate the Italian tariff policy into this model. The proposed model allows to evaluate the influence of each parameter on the system's performance. Other optimization research can be found in [127, 136]. Recently, some renewable energy, such as solar energy, has been implemented in the CCHP system to further reduce GHG emissions. In [137], a micro trigeneration system equipped with a solar system is studied. This system is integrated by a micro-turbine with output power of 5 kW and a LiBr/water absorption chiller. The heat source for the absorption chiller and the micro CHP system is a solar storage tank. Installing the solar system can efficiently increase the overall efficiency and consume less primary energy. Immovilli *et al.* [138] compare a conventional CCHP system with one based on solar energy. The configuration of a PV collector coupled with a vapor compression cooling system is verified to be the best commercially available solution. Besides the PV, they also propose two technical solutions for the solar CCHP to access residential applications, that is, concentrated sunlight all-thermoacoustic and hybrid thermo-PV systems. Beyond the above, some novel micro-scale CCHP structures are also proposed. Henning *et al.* [120] investigate a micro trigeneration system, whose air conditioning facilities integrate a vapor compression chiller and a desiccant wheel, for indoor air conditioning in a mediterranean climate. The research results show that, compared with conventional technologies, an electricity saving of 30% can be achieved. In [139], the authors investigate the performance of an absorption chiller, which is installed in a micro-scale BCHP system, under varying heating conditions. Huangfu *et al.* [5] introduce a novel micro-scale CCHP system which can be applied in domestic and light commercial applications. Evaluations and analyses in the literature show that this micro CCHP system enjoys good economic efficiency with a payback period of 2.97 years, which is quite short; also the electric load conditions determine the electric efficiency, which means that, compared with half load, the system can perform better when operating at full load.

1.4.2 Small-Scale CCHP Systems

Small-scale CCHP systems are the ones with rated size ranging between 20 kW and 1 MW. They have been widely used in supermarkets, retail stores, hospitals, office buildings, and university campuses. Different types of prime movers and refrigeration systems can be combined freely according to energy demands. Around the world, small-scale CCHP plants have been installed in many applications. A 500 kW biomass CCHP plant is installed in the Cooley Dickinson Hospital, Northampton, Massachusetts, which is a 55 742 m^2 hospital with 140 beds [140]. In 1984, the first boiler installed in this system was a Zurn-550 HP biomass boiler, which was fired by virgin wood chips. Then in 2006 and 2009, due to increased energy demands, an AFS-600 HP water/fire tube high pressure boiler, two 250 kW Carrier Energent micro steam turbines, and a 2391 kW absorption chiller were installed consecutively. This CCHP system has brought a lot of benefits to this hospital, especially the 99.5% particulate removal accomplished by the Multiclone separator and Baghouse. The East Bay Municipal Utility District (EBMUD), which was a publicly owned utility that provided a water service to portions of two counties in the San Francisco bay area, began to use a 600 kW micro-turbine CHP/chiller system at its downtown Oakland administration building in 2003 [141]. This system is composed of ten 60 kW Capstone micro-turbines and one 633 kW YORK absorption chiller. The total project cost $2 510 000, with a payback period estimated to be 6–8 years. Another small-scale CCHP application is in the Smithfield Gardens, which is a 56-unit affordable assisted-living facility in Seymour, Connecticut [142]. This system includes a 75 kW Aegen 75LE CHP module, an American Yazaki absorption chiller, and a Baltimore Air Coil cooling tower. With this system installed, the Smithfield Gardens can save 22% on its annual energy costs. With the pollution controlled by the Non-Selective 3-way Catalytic Reduction System, CO_2 and NO_x reductions can reach 32% and 74%, respectively. Vineyard 29, a winery located in St. Helena, California, installed a 120 kW micro-turbine/chiller system to reduce GHG emissions as well as toxins into the environment [143]. Two 60 kW Capstone C60 micro-turbine systems were installed to provide electricity and thermal energy. This a good example of waste heat cascade utilization. Through the heat recovery system, hot water is produced for the wine processing, and the other part of the thermal energy is adsorbed by a 70 kW Nishiyodo adsorption chiller to provide space cooling. In addition, a Dolphine pulsed power system is used in the EvapCo cooling tower. With a total capital cost of $210 000, the estimated payback period is 6–8 years, which means $25 000–38 000 per year. In [144], the authors provide experimental results for a real small-scale CCHP system operating at full load and partial load. This test plant, consisting of a 100 kW natural gas-powered micro-turbine and a liquid desiccant system, is installed at the Politecnico di Torino, Turin, Italy. Comparisons of primary energy savings (PES) among different prime mover load situations are made. The data shows that adopting the partial load strategy can cause an energetic performance decrease. Katsigiannis and Papadopoulos [145] conduct two case studies in the indoor Swimming Pool Building, and the Law School Building in the Democritos University of Thrace, Greece, to investigate their systematic computational procedure for assessing a small-scale trigeneration system. The procedure includes an indirect estimation of pertinent loads, indoor swimming pool heating, CCHP facility selection, system sizing, and economic evaluation. This work further verifies that the system performance mainly depends on the system size. Less cost and pollution can be readily observed from the simulation. Other applications and test work can be found in [146, 147, 148].

In their theoretical work, Chicco and Mancarella [149] summarize some key issues and challenges of the planning and design problems for a small-scale trigeneration system. Time domain simulations are conducted to assess each energy vector production within the system by introducing new performance indicators, that is, trigeneration primary energy saving (TPES), electrical-side incremental trigeneration heat rate (EITHR), thermal-side incremental trigeneration heat rate (TITHR) and cooling-side incremental trigeneration heat rate (CITHR). Other energetic, economic and thermodynamic analyses can be referred to [122, 150, 151]. In [122], the authors investigate an innovative natural-gas-based CCHP system, whose electricity, heating and cooling capacities are 126 kW, 220 kW and 210 kW, respectively. The gas-fired IC engine works in pairs with a liquid LiCl/water desiccant cooling system. The authors also give energetic and economic analyses, including the influence of the fuel and electric price, and index variations due to the plant cost, of this system. The proposed system has a payback period of around 7 years, and will provide $200 000–220 000 net present value after 15 years.

Some researchers focus on optimization problems involved in the small-scale CCHP system design. Abdollahi and Meratizaman [152] propose a multi-objective optimization method for a small-scale distributed CCHP system design. The environmental impact objective function is defined to be the cost. An economic analysis is conducted using the total revenue requirement (TRR) method. They adopt the genetic algorithm (GA) to find a set of Pareto optimal solutions; and apply the risk analysis to complete the decision-making to find the optimal solution from the obtained set. In [153], an optimization problem of the energy management in the CCHP system is solved by mixed integer linear programming (MILP). The solution aims to control the on/off status of system components. A comparison, with data collected from a 985 kW plant, is made between the proposed energy management and conventional management. The proposed optimal strategy allows a 1 year reduction of the payback period. Hossain *et al.* [154] present a design and the construction of a novel small-scale trigeneration system driven by neat non-edible plant oils, including jatropha and jojoba oil. The use of local available non-edible oil means this plant can run without depending on imported petroleum fuel, which results in a high economical efficiency. Moreover, GHG emissions can be dramatically reduced by using the rejected heat from the prime mover to provide cooling and heating.

1.4.3 Medium-Scale CCHP Systems

As mentioned, medium-scale CCHP systems are those with rated power ranges of 1–10 MW. From this level of rated size, CCHP systems begin to operate in large factories, hospitals, schools, and so on. A 4.3 MW CCHP plant has been serving the Elgin Community College, Elgin, Illinois, since 1997 [155]. The first phase of this plant, which was a 3.2 MW CCHP plant, was installed in 1997 to provide electricity, low pressure steam, and absorption cooling to main campus buildings. In 2005, due to campus expansion, the generation set and the absorption chiller were both expanded in the second phase. The prime mover in this system is a combination of four 800 kW Waukesha reciprocating engines and one 900 kW Waukesha reciprocating engine. Cooling is provided by one YORK 1934 kW absorption chiller and one Trane 2813 kW absorption chiller. The heat recovery equipment includes five Beaird heat recovery silencers and five Beaird exhaust silencers. The two phases cost \$2 500 000 and \$1 200 000, respectively. The payback period for the second phase is about 4 years with annual savings of around \$300 000. Another medium-scale CCHP application is that with a capacity of 3.2 MW which was installed in Mountain Home VA Medical Center, Mountain Home, Tennessee, in 2011 [156]. This medical center serves 170 000 military veterans in the surrounding states. The whole plant consists of one 3.2 MW dual-fuel engine generator set, fired by landfill bio-gas, two 1.8 MW back up diesel-fired engine generator sets, a heat recovery steam generator (HRSG), and a 3.5 MW absorption chiller. With this plant, the estimated cost savings over 35 years can be \$5–15 million. In the University of Florida, a 4.3 MW CHP plant began serving the Shands HealthCare Cancer Hospital in 2008 in order to solve the problem of increasing electricity and fuel prices, to reduce budget, and to reduce GHG emissions. The total installation cost \$45 million. This system, designed by Gainsville Regional Utilities (GRU), consists of one 4.3 MW combustion turbine, one 6.5 t/h HRSG, one 4.2 MW steam turbine centrifugal chiller, two 5.3 MW electric centrifugal chillers, and one 13.6 t/h packaged boiler. The 4.3 MW natural gas turbine provides 100% of the hospital's electric and thermal needs. By using this system, a total thermal efficiency of 75% can be achieved.

Other applications of medium-scale CCHP systems can be found in [157, 158, 159], to name a few.

Moreover, researchers are also concerned with theoretical research on medium-scale CHP/CCHP systems. In [160], in order to raise the energy efficiency, the authors propose a trigeneration scheme for a natural gas processing plant by installing a turbine exhaust gas waste heat utilization. This trigeneration system makes use of the rejected heat from the gas turbine to generate process steam in a waste HRSG. A double-effect LiBr/water absorption chiller is driven by the process steam to provide space cooling; another part of the process steam is used to meet furnace heating load and to supply plant electricity in a combined regenerative Rankine cycle. The measured CCHP power output is 7.9 MW. The expected annual operating cost savings can reach as high as $20.9 million with only 1 year payback period. In [161], the authors design a CCHP system for a business building in Madrid, Spain. The basic demands of this building are 1.7 MW of electricity, 1.3 MW of heating and 2 MW of cooling. By designing the operation strategy and optimizing facility capacities, the final design of the configuration is given to be an integration of three 730 kW IC engines, one 3 MW double-effect absorption chiller, one conventional chiller of 4 MW, and one 200 kW boiler for back up. On account of incorporating a thermal solar plant, the capital cost is €3.32 million, which is expected to be paid back in 11.6 years. Compared with conventional trigeneration systems, PESs in this plant increase a lot due to the incorporation of the thermal solar plant into the trigeneration plant. In [162, 163], the authors propose a methodology for thermodynamic and thermoeconomic analyses of a trigeneration system equipped with a Wartsila 18V32GD model 6.5 MW gas-diesel engine. This system is installed in the Eskisehir Industry Estate Zone, Turkey. Efficiencies of energy, exergy, Public Utility Regulatory Policies Act (PURPA), and equivalent electrical of the trigeneration system are determined to be 58.94%, 36.13%, 45.7%, and 48.53%, respectively. This CCHP system can also be transplanted to an airport to provide cooling, heating, and electricity. Other theoretical work can be referred to [164, 165].

1.4.4 Large-Scale CCHP Systems

Large-scale CCHP systems are categorized as those with output power of above 10 MW. This type of CCHP system can provide substantial electricity for industry use, and vast heating and cooling for universities and residential districts, which have a high population density. So far, to combat the problem of GHG emissions and increased prices of electricity and fuel, an increasing number of large-scale CCHP systems have been installed. The University of Michigan, Ann Arbor, Michigan, began to adopt the cogeneration system in 1914 [166]. Combined with absorption chillers, this 45.2 MW CHP plant consists of: six conventional gas-/oil-fired boilers from Combustion Engineering, Wickes, Murray and Foster Wheeler (a total of 453.6 t/h of steam capacity); three Worthington back-pressure/extraction steam turbine generators (rated at 12.5 MW each); two gas/oil solar combustion turbines (3.7

and 4 MW, respectively); and two Zurn HRSGs with supplemental gas firing (29.5 t/h each). The electricity production of this plant can rarely reach the maximum capacity, for the plant has to provide steam for other use, such as, in summer, the absorption chiller. The system installed saved the university \$5.3 million in 2004. In San Diego, California, the University of California at San Diego installed a 30 MW polygeneration plant in 2001 [167]. The 30 MW combined cycle is composed of two 13.5 MW Solar Turbines Titan 130 gas turbine gen-sets and a 3 MW Dresser-Rand steam turbine. The rejected heat is used to run a steam driven centrifugal chiller; to provide domestic hot water for campus use; and to run the steam turbine for additional electricity production. The whole system can achieve 70% gross thermal efficiency. Annually, by installing this system, \$8–10 million can be saved. In this site, an emission control system, that is, SoLoNOx^{TM}, is adopted to control the level of NO_x emissions to 1.2 ppm, which is much lower than the permitted 2.5 ppm. Another classic large-scale CCHP application is the plant installed in the University of Illinois at Chicago [168]. This plant, established from 1993 to 2002, is separated into two parts: the east campus system and the west campus system. In the east campus CCHP plant, two 6.3 MW Cooper–Bessemer dual-fuel reciprocating engine generators and two 3.8 MW gas reciprocating engine generators are installed as the prime mover. Cooling is provided by one 3.5 MW Trane two-stage absorption chiller, two 7 MW YORK electrical centrifugal chillers, and several remote building absorption chillers. The capital cost of \$25.7 million is estimated to be paid back in 10 years. PESs, CO_2 reductions, NO_x reductions, and SO_2 reductions can reach 14.2%, 28.5%, 52.8%, and 89.1%, respectively. In the west campus, because of the large energy demand in the hospital and several buildings, an additional 37.2 MW generation set, composed of three 5.4 MW Wärtsilä gas engines and three 7 MW Solar Taurus turbines, has been added. Besides the prime mover, an additional 7 MW absorption chiller was also installed in the west campus CCHP plant. With the capital cost of \$36 million, the payback period is estimated to be 5.1 years. Other applications that show the success of using the CCHP scheme in large-scale systems can be found in [169, 170, 171].

The comparisons among different system configurations can be found in Table 1.3.

Table 1.3 Comparisons among different system configurations

	Size	Preference
Micro-scale	<20 kW	Distributed energy system
Small-scale	20 kW–1 MW	Supermarkets, retail stores, hospitals, office buildings, and university campuses
Medium-scale	1 MW–10 MW	Large factories, hospitals, and schools
Large-scale	>10 MW	Large industries Waste heat can be used for universities and districts with a high population density

1.5 System Management, Optimization, and Sizing

Once the configuration of a CCHP system is determined for a specific application, the next step is to manage the energy flow reasonably and to select an appropriate facility capacity to achieve maximum cost and emission reduction. Actually, in some recent system optimization work, the operation strategy, power flow and facility size are optimized simultaneously. In this Section, some conventional and novel operation strategies, system optimization approaches, and sizing work will be introduced.

1.5.1 Conventional Operation Strategies

Two classical operation strategies for the CHP/CCHP systems are following electric load (FEL) and following thermal load (FTL) [172, 173], which can also be referred to as electric demand management (EDM) and thermal demand management (TDM) [174]. In the FEL strategy, the CCHP system first purchases the fuel to provide enough electricity for the building users. If the excess heat cannot meet the cooling and heating demand, additional fuel should be purchased to feed the auxiliary boiler to generate enough thermal energy. In the FTL strategy, the CCHP system first meets the thermal demand, including the cooling and heating, then if the electricity provided by the PGU cannot meet the building users' demand, additional electricity should be purchased from the local grid to compensate for the deficit. However, both the FEL and FTL strategies can inherently waste a certain amount of energy. This is because, for instance, when the CCHP system runs under the FEL strategy to provide enough electricity for the building users, if the thermal demand is less than the thermal energy PGU provides, the excess thermal energy will be wasted. It is a similar case for the FTL strategy. The comparisons and analyses of the two strategies are investigated in [33, 174, 175, 176, 177, 178, 179, 180], to name a few.

1.5.2 Novel Operation Strategies

In order to reduce the energy waste and to reduce primary energy consumption (PEC), annual total cost (ATC), and GHG emissions, it is necessary to design an optimal operation strategy. Due to different definitions of "optimal", the operation strategies designed are different. In [181], Liu *et al.* propose a novel operation strategy for the CCHP system by using the concept of "balance". By adjusting the electric cooling to cool load ratio between the electric chiller and absorption chiller, the balance point of users, electric demands, cooling demands and heating demands evolves to a balance space. Optimal operation strategy is designed to keep the energy balance. The case study shows that, running under the proposed operation strategy, the PEC, carbon dioxide emissions (CDE), and the ATC are much lower than those of the SP system. In [182], the author proposes an optimal operation strategy for an offline non-linear model, that is, TOOCS-off, of a CCHP system. This optimization model considers the electric and thermal load in each time interval, prices of electricity sold to costumers or purchased from utility, and prices of heating and cooling. In the cost function of the TOOCS-off model, the total economic benefit of this system is maximized during total daily operation time. In the constraints, facilities' thresholds and output upper bounds are considered simultaneously. A CCHP system with a capacity of 143 kW, equipped with a 450 kW auxiliary boiler, a 600 kW absorption chiller, and a 800 kWh content heat storage tank, is used to verify the feasibility of this offline model and the optimal operation strategy. Based on source PEC, Fumo and Chamra [183] analyze four CCHP system operation conditions, including power and cooling without requiring boiler operation (in spring/autumn), power and cooling requiring boiler operation (in summer), power and heating without requiring boiler operation (in spring/autumn) and power and heating requiring boiler operation (in winter). The results of this study can contribute to the design of the operation strategy to reduce undesired increase of energy consumption. In [175], the authors design an optimal operation scheme for a CCHP system by considering the PEC and emissions of pollutants besides the energy cost. The operation is optimized by an optimal energy dispatch algorithm. The evaluation of the performance of a CCHP system, operating under the proposed strategy, is conducted using five cities' realistic climate data. Cardona *et al.* [184] propose a profit-oriented optimal operation strategy, considering both the articulated energy tariff system and the technical characteristics of components. In [185], instead of the profit-oriented strategy and the primary energy-oriented strategy, the authors adopt an emission-oriented strategy in order to reduce GHG emissions. The control scheme in the proposed strategy is an on–off control, that is, if the level of GHG emissions is greater than a specific value, then the PGU should stop; otherwise, the PGU runs to meet the energy demand. A comparison of GHG emissions of the proposed strategy, profit-oriented strategy and primary energy-oriented strategy is made to show the effectiveness of the proposed operation strategy. In [186], the authors propose an FEL/FTL switching operation strategy for the CCHP system. An integrated performance criterion, including PEC, CDE and operational cost (COST), is used to determine the switching action between FEL and FTL strategies. However, the inherent energy waste still exists. In [187], by considering the uncertainties of the price of the purchased electricity, the delivered demand for electricity, and the marginal cost of self generation, the authors propose an operation strategy design method using a risk management approach. By using the risk metrics, the steam and gas turbine generated electric power, the benefits and costs can be forecast. Moreover, an optimal control tool, that is, the model predictive control (MPC), is also used in [187] to schedule the operation strategy. Mago and Chamra [172] propose an optimized operation strategy, which can be referred to as following the hybrid electric-thermal load (HETS). The analyses and evaluations show that, when operating under the HETS, a CCHP system can perform better in the aspects of PEC, operational cost and CDE, when compared with FEL and FTL strategies. In [188], the optimization of the operation strategy is formulated to be a linear programming (LP) problem with the objective function set to be the operation variable cost. This problem is constrained by capacity limits, equipment efficiencies, energy balance equations, and demand constraints. The obtained optimal operation strategy is classified in nine operational modes due to the price of electricity from grid, electricity sold back price, auxiliary heat, and waste heat. A thermoeconomic analysis, based on the marginal cost, is also conducted to investigate the relationship between the optimal operation mode and energy demands, as well as the prices of consumed resources. Aiming to maintain the system autonomy to ensure the grid reliability and to minimize excess power production, Nosrat and Pearce [189] propose a dispatch strategy for a PV-CCHP system, in which the thermal energy waste can be significantly reduced. Decision-making of this dispatch strategy depends on the output of the PV array and is separated into four steps. In each step, several operation conditions are analyzed to choose the strategy between FEL and FTL. The results show that an improvement of 50% can be achieved by using this dispatch strategy. Because the strategy is chosen from FEL and FTL directly, the inherent energy waste still cannot be avoided.

1.5.3 System Optimization

To optimize the system performance, a mathematical model should be constructed first to make use of the various optimization algorithms. In the literature, much work on the optimization has been done to investigate the CCHP optimization problem. Among these approaches, due to the on–off character of the components, mixed integer programming is the most widely used. Based on the concept of *superstructure*, the authors in [190] propose a systematic method to optimize the size of a CCHP system powered by natural gas, solar energy, and gasified biomass. Modeled by the mixed integer non-linear programming (MINLP) model, PESs, GHG emissions, and economic feasibility are optimized. They also point out that the trade-off between the economical and environmental concerns should be taken into consideration when designing a CCHP system. Following the previous work, which only concerns the monthly average requirement, Rubio-Maya *et al.* [191] take the hourly data, analysis, and energy storage system into consideration. This NP problem is solved by a generalized-reduced-gradient (GRG)-based algorithm. In [192], Buoro *et al.* model a trigeneration system to be an MINLP model. They propose a scheme of several buildings connected with each other. Thus, the optimal solution of this problem contains the prime mover's type and size, positions of district heating and cooling (DHC) pipelines, and the operation of each system component. Besides considering the thermodynamics of each system component, the objective function also takes the facilities' cost and DHC network cost into consideration. Moreover, the influence of various amortization periods on the optimal solution is also discussed. Li *et al.* [193] model and optimize a system by an MINLP model. Analyses in this literature show that the optimal facility size and the economic performance of the whole system mainly depend on the average energy demand. In [194], MILP is used to model and optimize a CCHP system with a thermal storage system installed and to minimize the ATC. In this reference, the effect of legal constraints and different operation modes on the optimal design is also discussed. In [195], the authors construct an MINLP model for increasing the power production in a small-scale CHP plant. This CHP plant is driven by a steam Rankine process fired by biomass fuel. Using the MINLP, due to the complicated decision-making process in the system, the optimization problem is modeled to be a non-convex problem. This problem is solved several times to filter out suboptimal solutions and to find out the most likely global optimal solution. This model is also tested on four existing CHP plants, in which the result shows that, by adding a two-stage district heat exchanger, a preheater, a steam reheater and a fuel dryer, the electric efficiency and power to heat ratio can be increased. Arcuri *et al.* [38] carry out a mixed integer programming model for the optimization of a CCHP system in a hospital. The optimization results, including short-term optimization and long-term optimization, give the optimal plant design, that is, facility sizes and running conditions. With the proposed optimization approach, the case study result shows that, by utilizing size optimized heat pumps, the trigeneration system can be improved in terms of economic, energetic and environmental aspects. Li *et al.* [196] thermoeconomically optimize a distributed trigeneration system by considering thermodynamic, economic and GHG emissions aspects. This optimization includes the system configuration and operation strategy. With the objective function set to be the system net present value (SNPV), MINLP is used to model the system and the GA is adopted to solve it. An optimal solution is found under different economic and environmental legislation contexts in Beijing, China. Rong and Lahdelma [197] model a trigeneration system by the LP model with three components' characteristics. The objective function is set to be a combination of production and purchase cost, and the carbon cost. This problem is solved by the Tri-commodity algorithm, which is 36–58 times faster than an efficient Simplex code. Using the PGU capacity as the decision variable, Wang and Fang [198] optimize a CCHP system by the GA. The objective function is set to be a weighted summation of PEC, ATC, and CDE. Wang *et al.* [32] design an optimal operation strategy by optimizing the capacity of the PGU, the capacity of the heat storage tank, the on–off coefficient of the PGU and the ratio of electric cooling to cool load using the particle swarm algorithm. All of the four decision variables are globally optimized, that is, fixed once determined. The authors of this reference also compare the result of [32] to that of another reference [33]. In [33], only the PGU capacity and electric cooling to cool load ratio are considered to be decision variables. The objective function, which includes PESs, annual total cost savings (ATCS) and CDER, is minimized by the GA. When compared with the GA, the particle swarm algorithm converges faster and the result is better. Sheikhi *et al.* [199] conduct a cost–benefit analysis of a CHP system aiming to maximize the benefit-to-cost ratio. With the benefit-to-cost ratio incorporated into the objective function, using the concept of *energy hub*, the size and efficiency of this CHP system is optimized using the evolutionary-algorithmic (EA) approach. Kavvadias and Maroulis [200] set up a multi-objective optimization problem for a trigeneration system, in which facilities, sizes, pricing tariff schemes and the operation strategy are to be optimized according to realistic conditions. Pointing out the drawbacks of traditional load following strategies, the authors propose a new load following strategy, that is, electric/heat equivalent load follow, which includes the continuous operation, peak shaving, electricity equivalent demand following, and heat equivalent demand following. The optimization problem is solved by the multi-objective

EA approach. Wang *et al.* [201] analyze the energy consumption and construct an environmental impact model, consisting of the global warming, acid precipitation and stratospheric ozone depletion, for an SP system and a CCHP system. The system capacity is optimized by the GA following the FEL strategy. In [202], the authors model a trigeneration system using a fuzzy multi-criteria decision-making model. Different configurations of trigeneration systems are compared with an SP system under this model. This fuzzy multi-criteria model can help to choose the optimal trigeneration configuration from technical, economical and some external (like the environmental) aspects. Piacentio and Cardona [203] propose a robust optimization method for a CCHP system based on energetic analyses. They point out and verify that, by considering the energetic behavior, instead of improving the efficiency of an optimization algorithm, the optimization result can be significantly improved. Moran *et al.* [133] propose a thermoeconomic modeling approach, including the monthly operation cost, monthly fuel consumption, overall system efficiency, and so on, for micro-scale CCHP systems in residential use. This model helps to choose the optimal prime mover type and capacity by taking the ratio of required heating and cooling loads to the required electric loads into consideration.

In recent years, a matrix modeling approach based on the *energy hub* has begun to be used to model and optimize CCHP systems. In [36], the authors use a comprehensive approach to model a CCHP system in a compact matrix form. By adopting sequential quadratic programming (SQP), the power flow and electric cooling to cool load ratio are optimized. The case study in [36] shows that, compared with conventional operation strategies, the proposed optimal power flow and operation strategy can well control the CCHP system to achieve less PEC, ATC, and CDE. In [204], Chicco and Mancarella propose a matrix modeling approach for a small-scale trigeneration system and optimize the operation strategy for it. The model is built by introducing the concepts of efficiency matrices, dispatch factors, interconnection matrices, and input-to-output connectivity matrix. A depth-first manner is adopted to construct the overall plant efficiency matrix. In the optimization problem, NP techniques are used to obtain an optimal solution. In 2005, Geidl and Andersson [205] proposed a general matrix modeling and optimization approach for an energy system with various energy carriers. The optimization problem is a non-linear, multi-variable and inequality-constrained problem, which can be solved by the NP algorithm. In a later work [206], they use the concept of *energy hub* [207] to model the system by introducing the dispatch factors and coupling matrix. The dispatch and power flow are optimized by using the Karush–Kuhn–Tucker (KKT) conditions in order to minimize the total energy cost. The marginal cost is used to solve the KKT conditions. Using the same modeling approach, the optimization problem is solved by MATLAB *fmincon.m* in [208]. Ghaebi *et al.* [209] model a CCHP system using the TRR model to exergoeconomically optimize the cost of the total system production. Diverse parameters, including the air compressor pressure ratio, gas turbine inlet temperature, temperature in the heat recovery system, steam pressure, and so on, are involved in this model. The GA is adopted to solve for the optimal solution. Effects of the decision variables on different objective functions are also discussed in their work.

1.5.4 Sizing

Besides system configuration, operation strategy design, another equally important problem involved in the CCHP system is the facility sizing. As we all know, in the configuration step, one chooses prime movers in a vague way, that is, no accurate rated power is chosen. For instance, when designing a small-scale CCHP system whose capacity is in the range of 20 kW–1 MW, what is the specific value on earth? An appropriate operation strategy must depend on the facility size. Except for the PGU, other facilities' sizes can be determined by the required output. However, the PGU size should not be too small, which will make a CCHP system degrade to an SP system and will cause more electricity to be purchased from the local grid; this size should also not be too large, for high capital cost and low partial load efficiency. In many cases, the facility sizing problem can be inherently included in the modeling and optimization procedure. However, once the system configuration and operation strategy are designed, only the facility is to be sized to make the whole system efficient, economical and environmentally friendly. In [210], the authors examine the influence of different prime mover sizes and different operation strategies on the performance of the CCHP system. They validate three different sizes of the natural gas reciprocating engines under three different classical operation strategies, that is, FTL, FEL and following constant load (FCL). Different from other work, they use the actual market prices of electricity and natural gas instead of the flat one to minimize the CCHP performance indicators, including cost, PEC, and CDE, by optimizing the engine size. They point out that the optimal prime mover size would vary according to different evaluation criteria (EC). Sclafani and Beyene [211] discuss the challenges of matching and sizing for the CCHP system, due to the strong and frequently varying load conditions, from both the operation-related and weather-related aspects. In order to mitigate the part-load issues and address the system flexibilities, the load profiling strategies are adopted to optimize the selection and sizing of the prime mover. Liu *et al.* [181] adopt the enumeration algorithm to obtain the optimal size of the PGU under the proposed "balance"-space-based optimal operation strategy. In [164], the authors investigate the impact of the carbon tax on the sizing and operation strategy design of a medium-scale CHP system based on the IC engine. The thermoeconomic approach (annual cost flow approach) is used to optimize the IC engine capacity. In this work, under three operation modes, that is, one-way connection, two-way connection and heat demand following, the gas engine and diesel engine are sized to minimize the net annual cost. Shaneb *et al.* [212] model a μCHP plant with a generic deterministic LP model to minimize the annual cost. During the process of the optimization, the optimal size of the CHP unit and the size of the back-up heater can be obtained simultaneously. The sizing of the μCHP system can be completed either by the maximum rectangle method, which is to cover the average energy demand instead of the peak demand, or by LP. Different sizing results according to different prime movers, including IC engine, stirling engine, SOFC, and PEMFC, are also presented. Harrod *et al.* [213] provide a sizing analysis on the wood waste biomass-fired stirling-engine-based CCHP system in a small office building. From their analyses, the characteristics of the prime mover, including the capacity and electrical efficiency, have a significant influence on the cost and PEC of the CCHP system. They also point out that the optimal engine size, which aims to reduce the cost, is always larger than that of the reference system, which can result in a larger PEC. Thus, the trade-off between the cost and the PEC should be taken into consideration when determining the optimal engine size. In [214], Ren *et al.* adopt the MINLP to model a residential CHP system, which includes a storage tank and a back-up boiler. In the optimization process, the CHP system capacity is selected and the operating schedules are determined in order to minimize the annual overall cost of the energy system. They also analyze the sensitivity of the natural gas prices, electricity prices, carbon tax rates and electricity buy-back prices on the optimal CHP system capacity. Besides the prime mover, the capacity of the storage tank is also optimized to reach a good trade-off between the flexible storage management and heat loss to the surroundings. Zhang and Long [215] also formulate the sizing problem of the CHP system as an MINLP problem constrained by the energy demands, facility performance characteristics and the power flow in the whole system. The objective function is set to be the ATC by considering the operation strategy. In [216], a gas-fired grid-connected cogeneration system, which includes an absorption chiller and a thermal storage system, is modeled as an MINLP model. The Newton–Raphson and conjugate method with tangent estimates and forward derivatives are used to search for the optimal facility size aiming to minimize the operational cost. The best feasible practical solution is determined by the dynamic programming principle. Financial analysis, including the payback period and internal rate of return, is also reported in this work. Similar to [190], Rubio-Maya *et al.* [217] use the superstructure concept to choose the optimal size, which includes the net power of the prime mover, cooling capacity of the thermally activated facility and fresh water capacity of the desalting unit, of a polygeneration system. The objective function is set to be the net present value, which is equally constrained by the energy and mass balance, and unequally constrained by the PES, GHG emissions and legal framework aspects, and is solved as an MINLP problem. Sensitive analyses based on the prices of electricity, fuel and water are also provided in this work. In [218], the aggregate thermal demand method (ATD_e method) is adopted to estimate the PES. In addition, the estimation of PES, which is used for the sizing problem, is based on the annual value. The PES strategy can combine both the economic and environmental considerations. The most advantageous aspect of this work is the simple calculation method, in which only a few representative global data are needed. In [219], using the concept of energy hub, Sheikhi *et al.* model the CCHP system optimization problem by an NP model. Aiming to achieve the maximum net benefit, the operation point of the energy hub and the size of prime mover, absorption chiller, auxiliary boiler and heating storage devices are optimized by solving the non-linear programming in GAMS software. In addition, a financial analysis, which includes the net present value and internal rate of return, is conducted using the technique of discounted cash flow analysis.

1.6 Development and Barriers of CHP/CCHP Systems in Representative Countries

1.6.1 The United States

The US government began to develop CHP/CCHP plants since 1978, when the PURPA was proposed. In the PURPA, utilities are required to interconnect with and purchase electricity from cogeneration systems, in order to give industrial and institutional users access to the grid and allow excess electricity to be sold back. With the help of the PURPA and the federal tax credit for CHP investment, the installed capacity of CHP/CCHP systems grew to 45 GW in 1995 from 12 GW in 1980. Due to the intense competition and instability in the electricity market, the development of CHP/CCHP plants slowed down in the 1990s. There was only 1 GW installed capacity increase from 1995 to 1998. To boost the development, together with the Environmental Protection Agency (EPA), the US Department of Energy (DOE) proposed the "Combined cooling heating & power for buildings 2020 vision", which aimed to double the installed capacity in 2010. Following the proposed document, the installed capacity grew significantly to 56 GW in 2001. Then in 2004, with a total installed capacity of 80 GW, the goal of 92 GW had been almost achieved. In 2009, after the Energy Policy Act in 2005, the installed capacity had reached 91 GW. The development trend of the US CHP/CCHP installed capacity from 1970 is shown in Figure 1.6 [220]. As of 2011, as shown in Figure 1.7, 30% CHP/CCHP installed capacity is used in chemical industries, 17% is used for petroleum refining, 14% for paper industries, 12% for commercial or institutional buildings, 8% for food manufacturing, 8% for other manufacturing, 5% for primary metals industries, and 6% for other industries. According to "The White Paper on CHP in a Clean Energy Standard" [221], the US DOE aims to have an 11% increase, from the current 9%, of

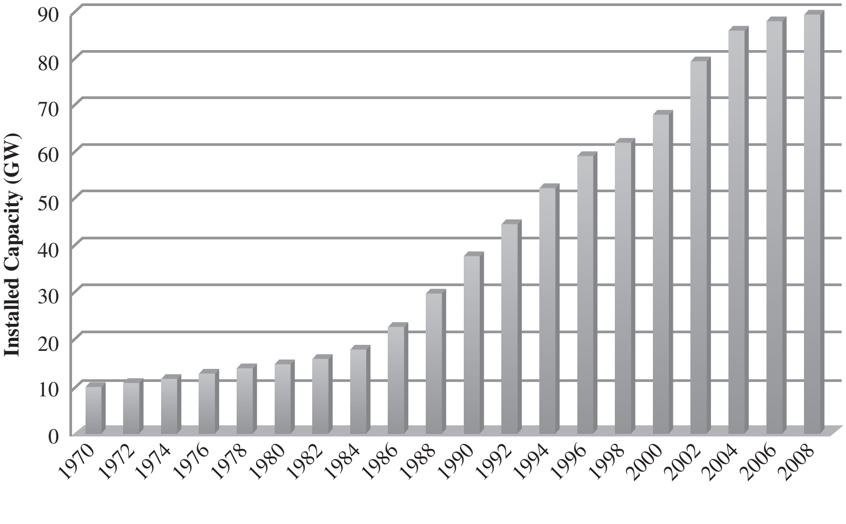

Figure 1.6 US CHP/CCHP development from 1970 [220]

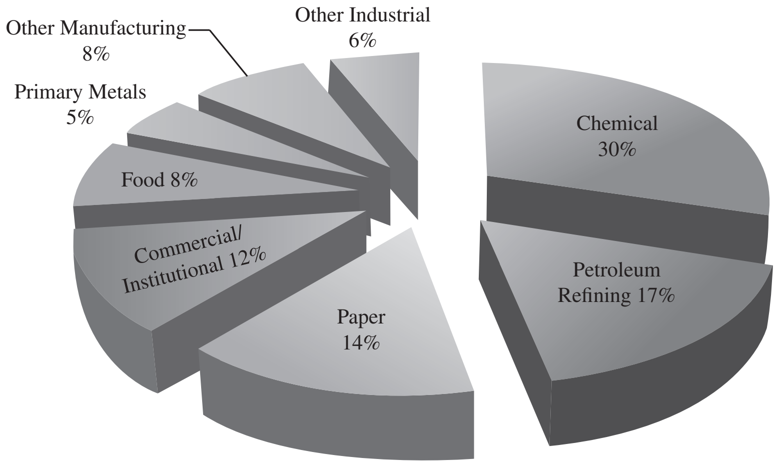

Figure 1.7 The installed capacity of CHP/CCHP plants classified by applications in the US

CHP share of the US electric power by 2030. By doing so, a 60% projected increase in US carbon emissions can be avoided; over 1 million new, highly skilled jobs can be created; and $234 billion in new investment can be generated.

However, there still exist some barriers to further development of CHP/CCHP plants in the US. The first one is the high capital investment of CHP/CCHP plants. A firm may not have sufficient budget to invest in such a high capital cost plant; or, if not sure about the payback of such a plant, it still cannot invest in it. Secondly, to keep a connection with the utility grid to supply power needs beyond the self generation capacity, extra charges will be made for this connection. This will no doubt reduce the money-saving potential of CHP/CCHP plants. Thirdly, non-uniform interconnection standards make it difficult for manufacturers to provide CHP/CCHP components. In addition, some policies, such as the Clean Air Act's New Source Review, only consider short-term carbon emissions instead of a long-term and overall vision. Because "the CHP/CCHP can increase onsite air emissions even as it reduces total emissions associated with the facilities heat and electricity consumption" [222], the development of CHP plants can be restricted by such regulations. Finally, further theoretical research, development, and demonstrations should be conducted to find out more efficient operation modes, system configurations, and system components.

1.6.2 The United Kingdom

In the UK, the number and installed capacity of CHP/CCHP plants increased dramatically from 1999 to 2000, during which time the UK government used methods of fiscal incentives, grant support, regulatory framework, promotion of innovation, and government leadership and partnership to support the development of CHP/CCHP. Before 2000, the installed capacity kept around 3.5 GW, while in 2000, it increased

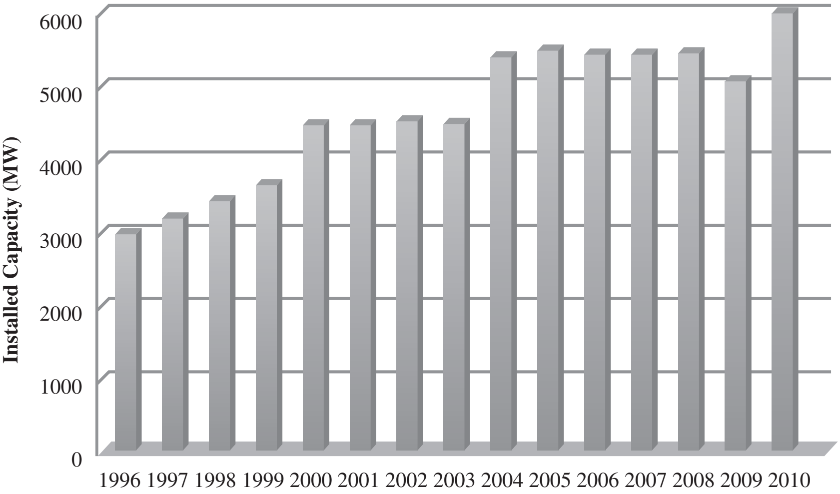

Figure 1.8 The CHP/CCHP installed capacity in the UK [223]

to 4.5 GW. From then on, the UK government continually drafted a series of policies to target achieving 10 GW *of good quality* installed CHP plants. By the end of 2010, the total installed capacity in the UK reached 6 GW, as shown in Figure 1.8 [223]. Classified by applications, as shown in Figure 1.9 [223], 38% of the installed capacity is used for oil and gas terminals and refineries, another 30% is used for

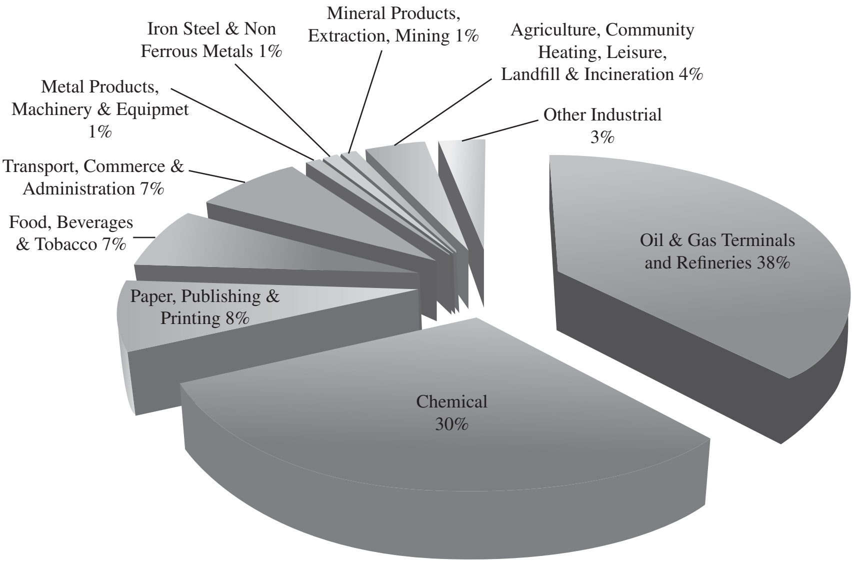

Figure 1.9 The installed capacity of CHP plants classified by applications in the UK [223]

chemical industries and only 4% is used for community usage, and so on. In [224], it is also pointed out that “the *of good quality* CHP will be a key technology in helping to deliver our carbon budgets while the grid decarbonizes, and will still play a pivotal role in providing secure and cost-effective energy supplies, particularly for industry. The government will continue to promote the development of *of good quality* CHP in the UK”.

Meanwhile, there are still some obstacles for CHP/CCHP to be further developed in the UK. The first one is the inconsistency between incentive frameworks and market signals. One significant characteristic of the UK market is price volatility. The differential between electricity and gas prices put the investment of CHP/CCHP in an uncertain situation. This issue may be addressed by the Climate Change Levy. Secondly, in theory, the establishment of the carbon market should directly support the expansion of CHP/CCHP capacity. However, due to the unstable carbon price and uncertain allocation arrangements of CHP/CCHP plants, this theory has not yet been verified. Only with a robust price signal and a stable carbon market, the direct relationship between the CHP/CCHP expansion and carbon market can be established. In addition, lacking locational signals for heat utilization also restricts the development of CHP/CCHP plants. Moreover, to achieve the peak efficiency, the heat transmission and distribution network should be completed. Finally, insufficient incentive to invest in heat distribution infrastructures also slows down the pace of CHP/CCHP development in the UK.

1.6.3 The People’s Republic of China

Due to the Reform and Open Up to the Outside World Policy, the rapid development of economics, technology, and industry leads China to be the well known second-largest energy consumer and carbon emitter in the world. To solve the problem of the increasing demand for primary energy, China has issued a series of policies, including the Energy Saving Law, the Renewable Energy Law, the Air Pollution Prevention Law, and the Environment Protection Law, to support the development of CHP/CCHP plants since the 1980s. In addition, accompanying those laws, some standards, for example, Energy Efficiency Standards for Buildings, and Energy Efficiency Standards for Appliances, and some dedicated funds, subsidies and discounted loans for energy efficiency investments have been implemented by the Chinese government. These steps make China the second-largest country in terms of installed CHP capacity. In 1986, the Notice on the Report Regarding the Work on Strengthening Urban District Heat Supply Management enhanced the urban district heating supply management. The China Energy Conservation Law, drafted in 1997, listed CHP as a key national energy conservation technology that should be encouraged. The 1998 Some Regulations for CHP Development considered the ratio between heat and electricity as an important indicator to define and approve new CHP. In 2004, the China Medium- and Long-Term Energy Development Plan considered CHP/DHC as an encouraging technology and named CHP as one of the 10 key national energy conservation programs. In 2006, the NDRC’s China Energy Conservation Technology Policy Outline recommended that CHP should take the place of small heating boilers; and they should be developed in large- and medium-sized cities in north heating areas. The 2007 Implementation Scheme of the National 10 Key Energy Conservation Projects further specified important applications and supporting policies for CHP. Another important policy that could boost the development of CHP/CCHP plants in China is the Industrial Guidance Catalogue for Foreign Investments drafted in 2007. This policy encouraged foreign investments and operations of CHP/CCHP power stations in China.

In 1990, the total installed CHP capacity in China was only 10 GW. After 10 years' construction and development, with an annual growth rate of 11.6%, a goal of 30 GW installed capacity was achieved in 2000. By 2005, almost 70 GW of capacity had been installed. Up to 2006, over 2600 CHP plants with over 80 GW capacity had been installed in China. The development trend is shown in Figure 1.10 [225]. The share of CHP capacity in thermal power generation in China is shown in Figure 1.11 [225].

With no doubt, CHP/CCHP is a promising solution for the energy shortages and air pollution problem, however, there are still some barriers to further developing CHP/CCHP plants in China. The first urgent problem to be solved is to reform the energy price policies. In China, even though the coal price, which has increased dramatically, is based on the market, the price of electricity, which has slightly increased, is decided by the government. Unbalanced increasing rates between the prices of coal and electricity severely restrict the development of CHP/CCHP in China. Besides the reform of energy price policies, heating and power sector reforms also need to be taken into consideration. Not only the economic and price aspect, but also some favorable fiscal and tax incentives should be proposed to support the construction of CHP/CCHP. In addition, since some newly built CHP projects are operating only in

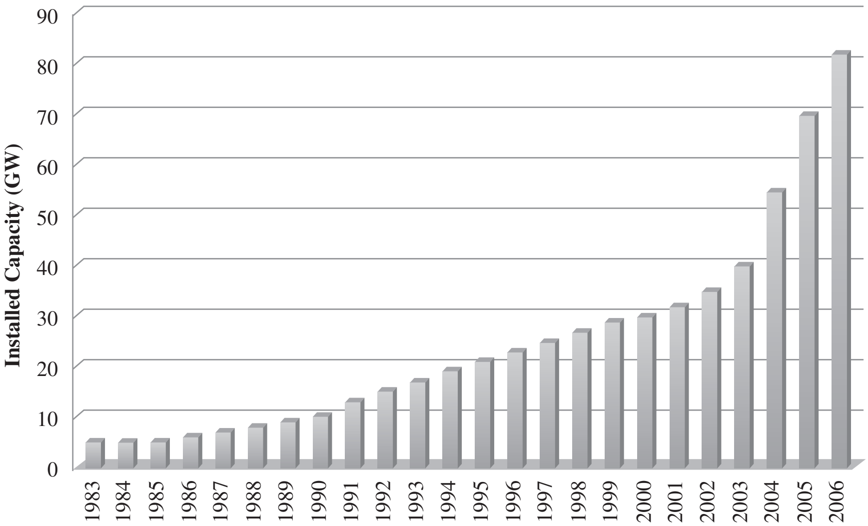

Figure 1.10 The installed capacity of CHP in China [225]

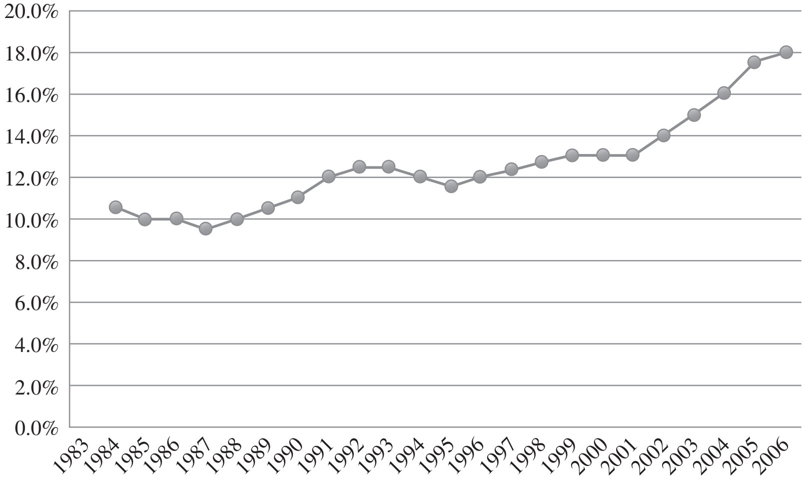

Figure 1.11 Share of CHP capacity in thermal power generation [225]

thermal generation mode after being established, energy efficiencies of these plants are significantly reduced. Thus, the monitoring and enforcement of the government energy price policies should be enhanced. Finally, due to an increasing number of large and more efficient CHP plants, some old, small but quite efficient CHP plants are being forced to shut down. Hence, policies that are suitable for the small but efficient units should be drafted to keep the overall efficiency.

1.7 Summary

This chapter elaborately presents the state-of-the-art of CCHP systems. The CCHP, which can provide the cooling energy by adopting thermally activated technology, is a concept extended from the CHP system. To construct an economical and efficient CCHP system, the type of facilities should be firstly determined according to local resources, and current and future energy market. Different types of prime movers and thermally activated technologies are introduced. The system configuration varies according to different usages, including commercial buildings, residential buildings, supermarkets, universities, hospitals, and so on. Some classical CHP/CCHP configurations classified by prime mover types and system capacities are also introduced in this chapter. With the determined facility type and system configuration, to achieve the optimal operation status, the operation strategy, power flow, and the facilities capacity should be optimized. The current research on the optimal operation strategy design, power flow optimization, and sizing problem are reviewed in this chapter. As many countries have begun to develop CHP/CCHP systems, the development history and current status of three representative countries, that is, the US, the UK, and the People's Republic of China, are presented. From these three countries, where the situations are different, some similar obstacles and solutions are discussed to further develop CCHP technology for the whole world. The high capital cost, government supporting policies, favorable fiscal and tax incentives, and further research and development should receive more attention. In the future development of CHP/CCHP systems, incorporating renewable energy is urged.

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